

## Variations in atmosphere-ocean solar absorption under clear skies: A comparison of observations and models

Brian J. Soden and V. Ramaswamy

Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

**Abstract.** Satellite observations of the clear-sky, atmosphere-ocean solar absorption are compared to simulations from a global climate model. Variations in solar absorption are analyzed under conditions of constant solar geometry to highlight spatially coherent features. From this analysis, the observed zonal and interannual variability in clear-sky solar absorption is shown to be substantially larger than that predicted by the model. Explanations for the greater observed variability are considered in terms of aerosols, surface wind effects, and water vapor.

### Introduction

Determining the amount of shortwave (SW) radiation absorbed by the Earth is fundamental for understanding its climate. Several recent studies have suggested that model calculations significantly underpredict the amount of SW radiation absorbed in the Earth's atmosphere (Cess et al., 1995; Ramanathan et al., 1995). This discrepancy was attributed to shortcomings in our current knowledge of the absorption by clouds, whose role in absorbing SW radiation has been of long-standing debate (Stephens and Tsay, 1990; Li et al., 1995). Similar discrepancies in model estimates of SW absorption have been identified in other studies, but attributed to clear-sky aerosols (Barker and Li, 1995) and water vapor (Arking, 1996) rather than clouds. Some field measurements also find discrepancies under clear skies (Charlock et al., 1996), while other studies find good agreement when aerosols are included (Waliser et al., 1996; Cess et al., 1996; Conant et al., 1997).

In this report satellite observations of the clear-sky, top-of-atmosphere (TOA) SW absorptivity  $A$  are obtained from the Earth Radiation Budget Experiment (ERBE; Barkstrom et al., 1989). Here  $A$  is defined as  $A = (S\downarrow - S\uparrow)/S\downarrow$ , where  $S\uparrow(S\downarrow)$  is the clear-sky upward (downward) SW flux at the TOA, or equivalently  $A = (1 - \alpha)$ , where  $\alpha$  is the clear-sky TOA albedo. The ERBE measurements are compared to observations of column integrated water vapor ( $W$ ; Greenwald et al., 1993) and surface wind speed ( $V$ ; Wentz, 1989) from the Special Sensor Microwave Imager (SSM/I), and aerosol optical depth ( $\tau$ ) from the Advanced Very High Resolution Radiometer (AVHRR) using the phase-2 retrieval of Stowe et al. (1997). This study focuses on periods of 1987 and 1988 when all three satellite data sets are all available and will be restricted to ocean surfaces since  $W$ ,  $V$ , and  $\tau$  are not retrieved over land. The observed variability is then compared to that predicted by a Global Climate Model (GCM; Wetherald et al., 1991) integrated using observed SSTs for 1979-1988.

If absolute values of SW absorption are compared, rather than variations, the level of agreement between the GCM and observations is relatively good (e.g., Fig. 1) and similar to that found by Kiehl et al. (1997). Such comparisons are largely a reflection

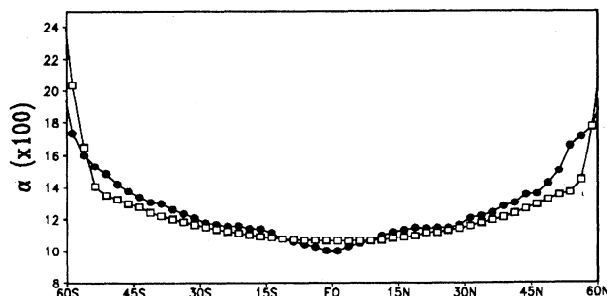
of the model's ability to compute the surface albedo and its dependence on solar zenith angle. By examining the variability in  $A$  under constant solar geometry, this study performs a more critical assessment of the model's skill in accounting for atmospheric variables which influence the TOA SW absorption.

### Observed and GCM-Simulated SW Absorptivity

The absorbed SW radiation at the TOA is determined by absorption both within the atmosphere and at the surface. The ocean surface albedo depends strongly on the solar declination angle which varies substantially with latitude and season. Therefore, to reduce the impact of changes in ocean albedo it is useful to consider variations in  $A$  under conditions in which the solar declination angle is constant. For this purpose we consider two sources of variability: (i) interannual variations associated with the 1987 El Niño/Southern Oscillation (ENSO) and (ii) zonal variations around individual latitude belts. It will be shown that both analyses lead to similar conclusions.

Figure 2 depicts the zonal deviations in the GCM-simulated (top) and satellite-observed (middle, bottom) quantities. The zonal deviations are computed by subtracting the zonal-mean from the value at each grid location; i.e.  $\delta A = A - [A]$ , where  $[A]$  denotes the zonally-averaged value of  $A$ . All quantities are annual means for 1988. The analysis is restricted to latitudes equatorward of  $45^\circ$ , since ERBE clear-sky observations poleward of this region are poorly sampled due to persistent cloud cover. In the GCM, coherent large-scale patterns are evident with regions of positive  $\delta A$  coinciding with regions of positive  $\delta W$  and vice-versa. Other quantities affecting  $A$  (e.g., ocean albedo) do not vary zonally in the GCM, consequently the GCM-simulated  $\delta A$  is solely due to zonal variations in absorption by water vapor. The correlation between GCM-simulated  $\delta A$  and  $\delta W$  is  $r_{AW} = 0.96$ , indicating that increased water vapor is associated with increased absorption of SW radiation. (To reduce the sensitivity to outlying data, all correlation coefficients are computed using the Spearman rank method and all slopes are computed using least absolute deviations).

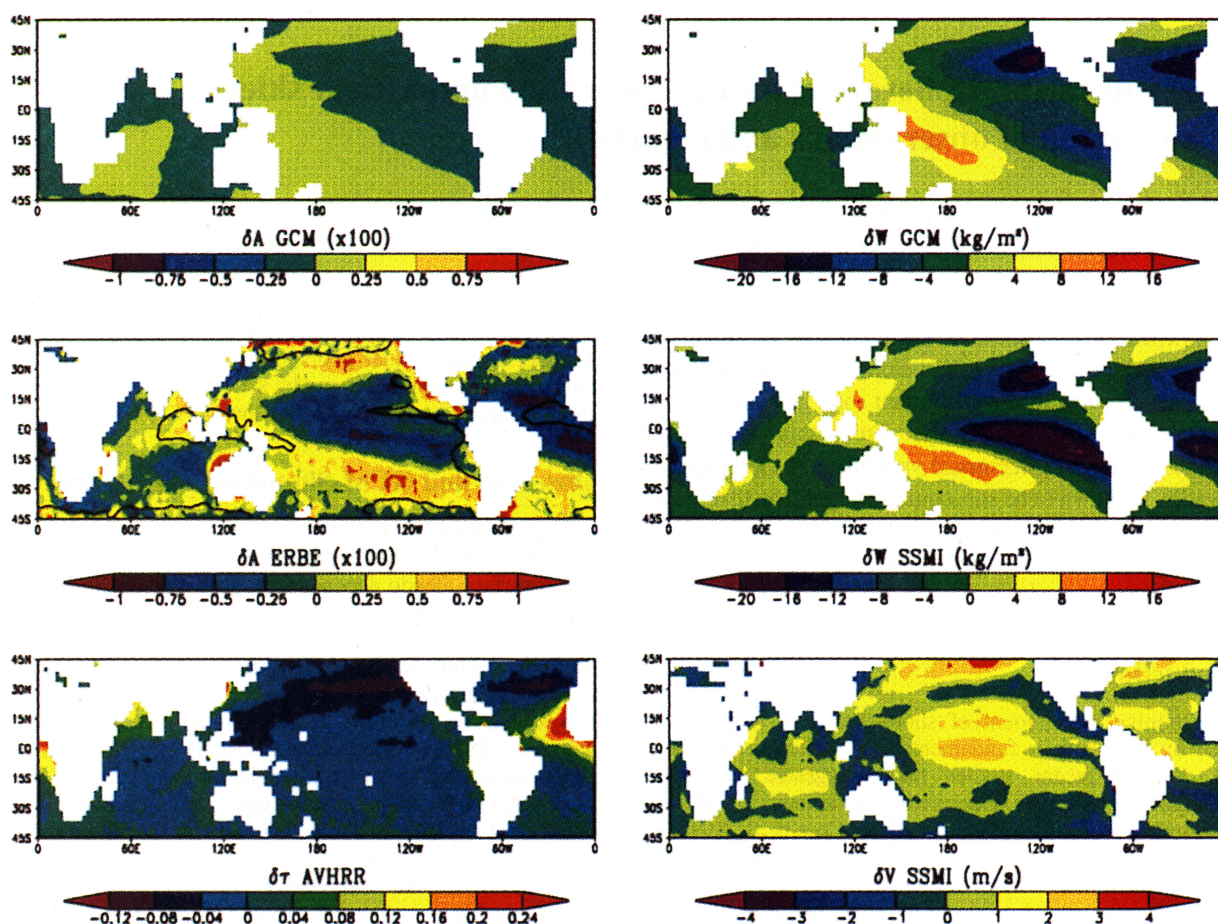
The observed pattern of  $\delta A$  also resembles the pattern of  $\delta W$  (Fig. 2, middle) such that increased moisture coincides with increased SW absorption. The lower correlation ( $r_{AW} = 0.43$ ) with



**Figure 1.** The zonal-mean TOA albedo (in %) from ERBE (filled) and the GCM (open).

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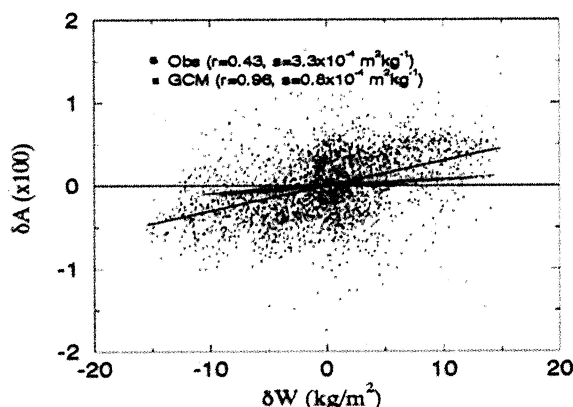
**Figure 2.** The zonal deviation in annual-mean: GCM absorptivity  $\delta A$  (top left), GCM water vapor  $\delta W$  (top right), observed absorptivity  $\delta A$  (middle left), observed water vapor  $\delta W$  (middle right), observed aerosols (bottom left), and observed wind speed  $\delta V$  (bottom right). The black line in the observed  $\delta A$  delineates regions which averaged fewer than one clear-sky observation every other day over the 1-year period and are excluded from the regression in Figure 3.

respect to the GCM's partly reflects the greater small-scale spatial variability in the ERBE  $\delta A$ . The observed variability in  $A$  is much larger than that predicted by the GCM, even for similar changes in  $W$ . Linear regression of  $\delta A$  versus  $\delta W$  (Fig. 3) yields a slope of  $3.3 \times 10^{-4} \text{ m}^2 \text{ kg}^{-1}$  for the satellite observations (black dots), but only  $0.8 \times 10^{-4} \text{ m}^2 \text{ kg}^{-1}$  for the GCM simulations (red dots). Note that any underestimate in atmospheric SW absorption would be largely compensated for by an increase in surface absorption. This must be considered when appraising the relatively small magnitudes of  $\delta A$  presented here.

The SW radiative transfer parameterization used in the GCM is based on that developed by Lacis and Hansen (1974). This parameterization slightly underestimates the SW absorption by water vapor compared to line-by-line (LBL) results (Foucart et al., 1991). The dependence of  $\delta A$  on  $\delta W$  predicted by this model was compared to the GFDL LBL algorithm (Ramaswamy and Freidenrich, 1992) and found to be in good agreement (slope of  $\delta A/\delta W$  within 10% of LBL). Thus, the differing slopes in Figure 2 can not be attributed to a water vapor-related deficiency in the GCM's radiation scheme.

However other factors which influence  $A$ , such as tropospheric aerosols, are not accounted for by the GCM. Consider the observed variations in aerosol optical depth  $\delta \tau$  (bottom left). Regional signatures of aerosol radiative effects are clearly present in the ERBE data. Enhanced SW absorption (reduced reflection) over the north Pacific and north Atlantic oceans co-

incides with bands of low optical depth. Likewise, enhanced aerosols over the equatorial Atlantic and Arabian Sea coincide with reduced SW absorption (enhanced reflection). However the agreement between  $\delta A$  and  $\delta \tau$  is less impressive over the Southern Hemisphere where variations in SW absorption occur in the absence of any corresponding changes in optical depth.



**Figure 3.** A plot of  $\delta A$  versus  $\delta W$  for the observations (black) and the GCM predictions (red).



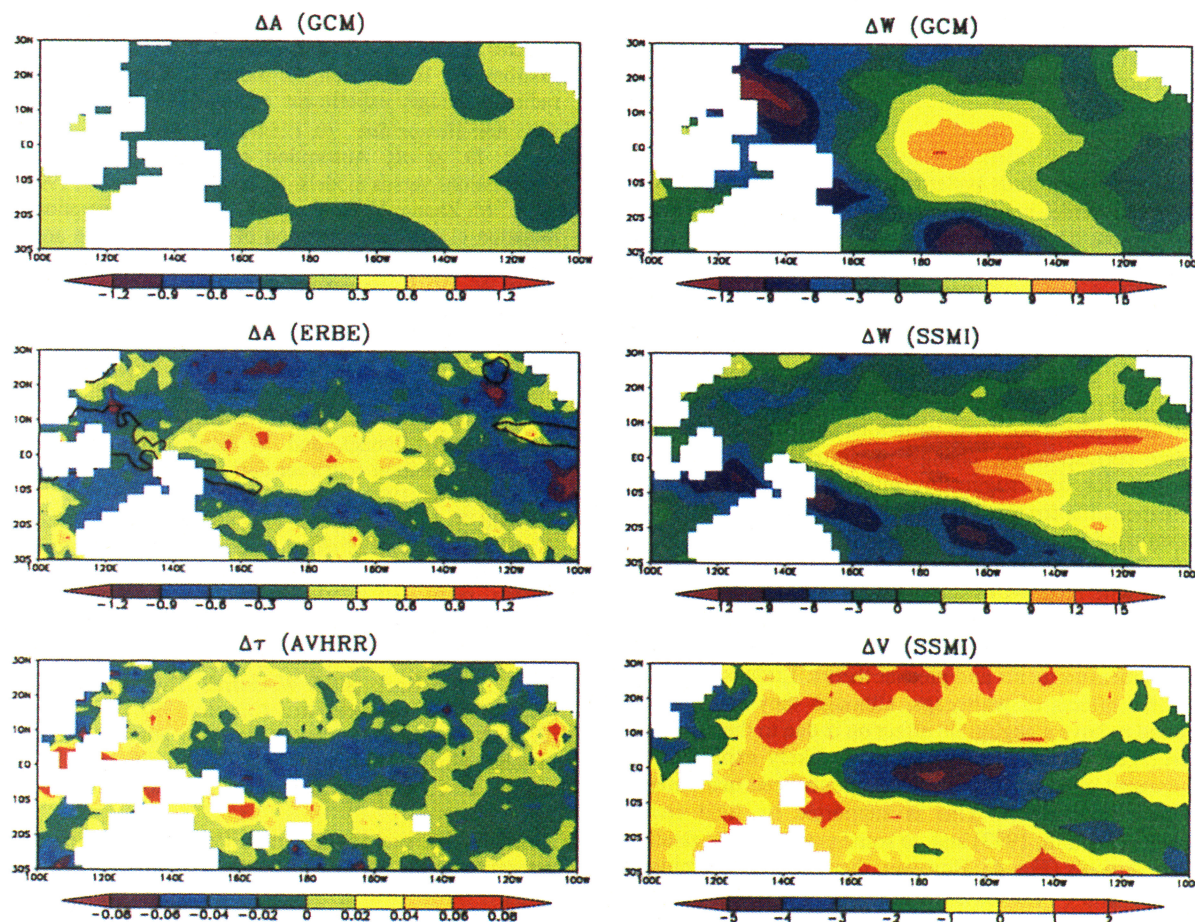


Figure 4. As in Figure 1 except for interannual differences rather than zonal deviations.

Variations in  $A$  can also arise from wind-induced changes in ocean surface albedo through waves or white caps. Observations of the zonal deviations in surface wind speed ( $\delta V$ ) bear some resemblance to the variations in SW absorption. Enhanced wind speeds are observed over large regions of the tropical Pacific and Atlantic near areas of reduced SW absorption. The spatial correlation between  $\delta A$  and  $\delta V$  is negative ( $r_{AV} = -0.44$ ), indicating that increased wind speeds tend to be associated with decreased SW absorption. However, both observational (Payne, 1972; Simpson and Paulson, 1979) and theoretical studies (Preisendorfer and Mobley, 1986; Hansen et al., 1983) suggest that increased wind speed decreases the ocean albedo (although they neglect whitecaps). Therefore current understanding of wind-induced changes in ocean albedo is of the wrong sign to explain the observed variations in  $A$ . The dependence of marine aerosols on surface wind speed may provide a more likely explanation for the similarity between  $\delta A$  and  $\delta V$ . It is widely documented that the concentration of marine aerosols, particularly sea-salt, increases with increasing wind speed (e.g., O'Dowd and Smith, 1993). For example, regions of low  $\delta \tau$  over the north Pacific and Atlantic oceans coincide with regions of low wind speed (Fig. 2). However, such agreement is not evident over the south Pacific and Atlantic oceans, perhaps indicating that sea-salt is underestimated in this region by AVHRR. We also note that biases in the observed  $\delta A$  could conceivably result from windspeed-dependent errors in the ERBE retrieval of SW fluxes (e.g. radiance to flux conversion). Unfortunately, little is known about the sign or magnitude of such errors.

A similar discrepancy between observed and GCM-simulated variations in  $A$  is also evident in the interannual variations of

these quantities. Figure 4 (top) depicts the changes in SW absorptivity  $\Delta A$  and precipitable water  $\Delta W$  associated with the 1987 ENSO for the GCM simulations. The differences, computed by subtracting the time-average of Sept. to Nov. 1987 from Sept. to Nov. 1988, represent a warm phase minus cold phase anomaly. The analysis is restricted to the tropical Pacific where the ENSO signal is most prominent. For the GCM, a coherent pattern is evident with increased absorption over the central and eastern equatorial Pacific bordered by decreased absorption to the north, south and west. The GCM's ocean surface albedo depends only on solar zenith angle and therefore does not contribute to interannual changes in  $A$ . Rather,  $\Delta A$  results from changes in SW absorption by water vapor as evidenced by their high correlation ( $r_{AW} = 0.96$ ).

The observations also exhibit a coherent pattern of  $\Delta A$  which is similar to the observed pattern of  $\Delta W$  (Fig. 4, middle). However, for similar values of  $\Delta W$  the magnitude of  $\Delta A$  is again typically a factor of four larger in the observations than in the GCM. Thus, for the observed  $\Delta A$  to be solely due to  $\Delta W$  would require a substantial shortcoming in our current understanding of solar absorption by water vapor (e.g., Arking, 1996). However, changes in both aerosol optical depth  $\Delta \tau$  and wind speed  $\Delta V$  (Fig. 4, bottom) closely coincide with  $\Delta A$ . The agreement between  $\Delta A$  and  $\Delta \tau$  indicates that regions of increased optical depth are associated with decreased SW absorption and vice-versa ( $r_{A\tau} = -0.44$ ). This suggests that changes in marine aerosols are contributing, at least in part, to the greater observed variations in  $A$ . Furthermore, the similarity between  $\Delta \tau$  and  $\Delta V$  again suggests a physical link between changes in surface wind speed and marine aerosols that is consistent with the occurrence of sea

salt. Although the possibility that wind-driven changes in the ocean surface albedo could introduce similar biases in the retrieval of both  $\Delta A$  and  $\Delta \tau$  can not be ruled out.

## Summary

This investigation finds systematic discrepancies between the observed and model-predicted variability of atmosphere-ocean SW absorption. The discrepancies identified here occur under clear-sky conditions and are consistently manifest in both the interannual and zonal variations. We infer three possible explanations for the discrepancies:

(i) *Aerosols*. The presence of aerosols seems likely to contribute to the greater observed variability in  $A$  relative to the GCM. This is particularly evident in  $\Delta A$  (Fig 4). However, there are also areas where observed variations in  $A$  are not associated with any corresponding change in aerosols (e.g. Southern Hemisphere for  $\delta A$ ), suggesting either that aerosols are not solely responsible for the discrepancy or that their variability is underestimated in current satellite measurements.

(ii) *Surface winds*. The larger observed variability in  $A$  is also associated with changes in surface wind speed which can alter the ocean surface albedo. However, the sign of the relationship between wind speed and ocean albedo contradicts that deduced from both measurements and present theory. Little is known regarding the effects of whitecaps, although they are generally considered to have a negligible effect on  $\alpha$  due to their small areal coverage (Monahan, 1970). A more likely explanation is that increased wind are associated with enhanced marine aerosols which decrease  $A$ . This is supported by field studies (O'Dowd and Smith, 1993) and, to some extent, by the satellite-observed aerosols (Fig. 4). However, there is little resemblance between  $\delta V$  and  $\delta \tau$  for the Southern Hemisphere (Fig. 2), perhaps reflecting a difficulty in remotely sensing aerosols for this region. If true, this could explain some of the large observed variations in  $\delta A$  that are not present in the GCM or in the satellite aerosol measurements. The possibility of wind-speed dependent errors in the ERBE retrieval of SW fluxes should also be considered.

(iii) *Water vapor*. The larger observed variability in  $A$  is also associated with changes in water vapor, suggesting that the discrepancy may, in part, be attributable to a systematic underestimate of SW absorption by water vapor in current radiative transfer models. The extent to which water vapor is responsible for the discrepancy (if at all) can not be assessed here. While this explanation is unlikely, the similarity between the observed variations in  $A$  and  $W$ , suggests that its quantitative role warrants further scrutiny alongside aerosol and surface wind effects. Given the difficulty of unraveling the relative contributions of  $\tau$ ,  $V$ , and  $W$  to the observed variations in  $A$ , in-situ measurements of all four quantities will like be needed to fully resolve this dilemma. We note that analyses of recent field measurements (Conant et al., 1997; Zender et al., 1997) show no evidence to suggest that the magnitude of clear-sky water vapor absorption is deficient in existing models.

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Brian J. Soden and V. Ramaswamy, NOAA/GFDL, PO Box 308, Princeton, NJ 08542. (e-mail: bjs@gfdl.gov; vr@gfdl.gov)

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